Analysis of the Effect Environmental Temperature Change has on the magnetic field Strength of Permanent Magnet Assemblies Using Experimental Methods

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Abstract

This paper aims to establish the exact relationship between Gauss Level and Temperature for a permanent magnet assembly. Magnetrons require a magnetic field to constrain the thermo-electrons emitted from the cathode to form a space charge cloud. The thermo-electrons would simply dissipate at the earth plane rather than form a space charge cloud without this magnetic field. Hence, to ensure optimum performance and consistency of the magnetron, the magnetic field must be calibrated. To calibrate the magnetic field, electromagnets are commonly used as they are highly flexible but they create additional variables such as cost and complexity. After thorough checks to ensure they have the right magnetic field strength, alternative approach is to use permanent magnets. There is some difficulty is measuring field strength accurately using permanent magnets as they are subject to environmental factors such as temperature which affect their magnetic properties. There is the need to compensate for these environmental factors during measurement to ensure accuracy and therefore correct running of a magnetron. Test data was generated through an experiment which was carried out on a permanent magnet sample cycled in temperature while the magnetic field was measured at periodic intervals. A mathematical model generated from test data can then be used for compensation. The Gauss probe used to measure magnetic field was temperature cycled independently to determine the measurement error and a calibration magnet was cycled to validate the data collected in the first experiment.

1. INTRODUCTION

The atomic structure of the elements which make up a magnet must be studied to understand the effects of temperature which could either be the strengthening or weakening of the magnetic field of that magnet[8]. A total magnetic moment for the permanent magnet is a sum total of the atomic magnetic moments. The total magnetic moment per unit volume is the magnetization, M. As a result of the driving force of an externally applied magnetic force, H and the internal magnetization, M we see a resulting property known as the magnetic flux density, B [8]. Where demagnetisation due to shape dependent effects are neglected,

$B = \mu_0(H + M)$ (1)

Where μ_0 is an arithmetical constant.

A linear relationship exists between internal magnetisation, M and External Magnetic field, H as shown in equation (2)

$M = {}^{0}_{x}H$ (2)

The material is paramagnetic where x is positive and diamagnetic where x is negative. There is also a linear relationship between the magnetic flux density, B and the external applied magnetic field, H as shown in equation (3)

$B = \mu H = \mu_o (1 + x) H = \mu_0(H + M)$ (3)

The magnetic permeability is

$\mu = (1 + x) \mu_0 = \mu_r \mu_0$ (4)

Where μ_r is the relative permeability and μ_0 is the free space permeability.

$\mu_r \sim 1$ For paramagnetic and diamagnetic while$\mu_r \gg 1$ for ferromagnetic.

The magnetic permeability,

$$\mu = (1 + x) \mu_0 = \mu_r \mu_0$$

Where μ_r is the relative permeability. x is susceptibility. Where $\mu_r = 1$, the material does not react to the magnetic field by magnetizing and $\mu_r > 1$ shows the material will magnetize when subject to a magnetic field.

The reaction of various magnets to temperature varies. According[7], Alnico magnets have the best strength stability trailed by SmCo, NdFeB, and then ceramic. NdFeB magnets possess the highest resistance to demagnetization (coercivity), but the largest change with temperature. Alnico magnets have the lowest resistance to demagnetization, but the smallest change with temperature. Alnico has the highest service temperature followed by SmCo, ceramic and then NdFeB. The strongest magnets are Neodymium magnets[1] which have a high power to volume and weight ratio and low cost per unit of strength. Neodymium magnets can be used in very challenging applications and survive sizable external magnetic fields due to their high resistance to demagnetisation[1]. Permanent magnets have various applications however; this paper focuses on its application with regards to radiotherapy systems. The radiotherapy system utilises a magnetron coupled with a permanent magnet. After supply, the magnets are inspected and then provided for use. During Inspection of the magnetic field strength variations have been observed. The Variations observed are of a single permanent magnet assembly on two different days. Literature for Neodymium magnets shows that ambient temperature changes can lead to small, but measurable changes in magnetic field strength, on the order of 0.08-0.12%/°C [6]. The general trend for this material is that magnetic field strength decreases with increasing temperature. The specified value for the magnetic field on-axis centre gap is 1560 +/- 20 Gauss (1.282% tolerance), so depending on the change in temperature, it possible that the magnets could be out of specification when measured during inspection [7].

2. METHODOLOGY

- The temperature was raised in 4°C increments at a ramp rate of 1°C per minute.
- Each temperature increase was followed by a 1 hour stabilisation step to allow for the entire mass of the assembly to stabilize at the same temperature. This time was recommended as it was believed that the high density of the material would stop it coming up to the target temperature within a shorter stabilization period.
- The Magnetic Field Strength was measured every 10 minutes within the hour step to generate an average.

Note: From the transverse probe data sheet the temp coefficient of the probe is +/- 0.09 - 0.13 G/°C. This means as the temperature of the probe increases during the temperature cycling there will be a potential measurement error of 0.09 - 0.13 G [3, 4, 5].

3. EXPERIMENT

3.1 ASSEMBLED MAGNET EXPERIMENT

An assembled magnet was cycled from 15 to 35°C in a Thermatron environmental cycling chamber. The Magnetic field strength level was measured using a Lakeshore Gaussmeter Transverse probe connected to a Lakeshore 425 Gaussmeter. The probe is then placed into the Nylon measuring Jig which will then be placed into the Magnet Assembly (See Figure 1). The probe lead fed out of the chamber via the feed hole in the side of the chamber into the meter which will sit next to the chamber externally. The temperature of the chamber was then load driven. This meant that a thermocouple attached to the load will act as the temperature reference for the chamber control system; in this case the right pole of the assembly was used. Additional thermocouples were used to measure chamber air temperature, Left Pole temperature and Probe temperature. This can be seen in Figure 1.

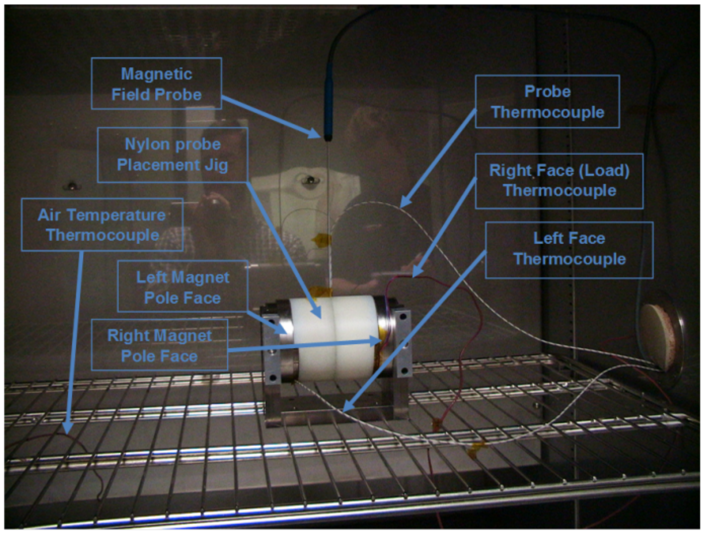

Figure 1: Experimental test set up 1

3.2 GAUSS METER PROBE EXPERIMENT

In order to validate the experiment and ensure accuracy of results, a second experiment was carried out to establish to what extent temperature had on the Gauss probe measurements during the original experiment. The set up shown in figure 2 was much the same as the first experiment, the difference in this set up instead of the probe being mounted in the permanent magnet assembly it is placed next to a small piece of magnetic ore. This purpose of this is to generate a small but measureable magnetic field (0.0137kG @ 25°C) that can be used as a bias when measuring the change in the probe measurements. The reason for simply not placing the probe by its self in the chamber is that at back ground the probe will be at its very lower limit of measuring capacity this would mean it would be difficult to accurately discern and measure change due to temperature. Any concerns about the magnetic field being produced by the magnet being altered by the temperature change are not warranted because as seen in the first experiment a maximum of a 1.7% shift was seen, in the small magnetic field produced in this experiment that would result to a 2.3 Gauss shift. With this offset known it can be factored into the results if a shift of this magnitude is seen. A thermocouple is attached to the Gauss meter probe so that the experiment can be load driven, this means driven from the temperature of the probe rather than the air temperature as seen in figure 2.

Figure 2: Labelled Photo of Test Set up

The method used during the second experiment is as follows,

- The temperature was raised in 2°C increments at a ramp rate of 1°C per minute. With a starting value of 15°C and a finishing value of 35°C.
- Each temperature increase will be followed by a 1 minute stabilisation step to allow for the entire mass of the probe to stabilize at the same temperature and therefore give a more accurate reading. This is only a short step due to the very small thermal mass of the probe.
- The Magnetic Field Strength will be measured at the end of each 1 minute stabilization period. The air temperature and the load temperature are also recorded at this time.

3.3 CALIBRATION MAGNET EXPERIMENT

The magnet being tested is a calibration magnet; this means it is used as an exact reference of magnetic field strength during test set up and the creation of procedures. The Magnet is not in an assembly of any type it is simply a large block of Sumerian cobalt with a precise calibrated magnetic field strength at the specific measuring point. The purpose of measuring this magnet is to see how much the magnetic field strength is altered without at effect of the stainless steel assembly. The magnet is made of a different material but the information gained from this experiment will still show if a nonlinear pattern is formed by the results or if there is a severe difference in these results in comparison to the first experiment results.

The setup is similar to the first 2 experiments in the fact it uses the gauss probe fed through into the chamber to measure a magnetic field, in this case it is placed into the slot in the calibration magnet. The point of this slot is that it locates the probe perfectly so there is appoint with an exact measurable magnetic field strength. The magnet was placed (as seen in figure 3) on its side so the slot was facing out sideways in parallel with the base of the chamber. This is so that undue stress was not placed on the probe from the weight of the lead or any force exerted on the lead while fans etc. were blowing in the chamber during operation. A thermocouple has been placed next to the slot for the Gauss meter probe, ideally the thermocouple would be better placed at the bottom of the probe slot but that is not feasible due to the slot size. The control for the chamber will be load driven, so the temperature of the magnet block

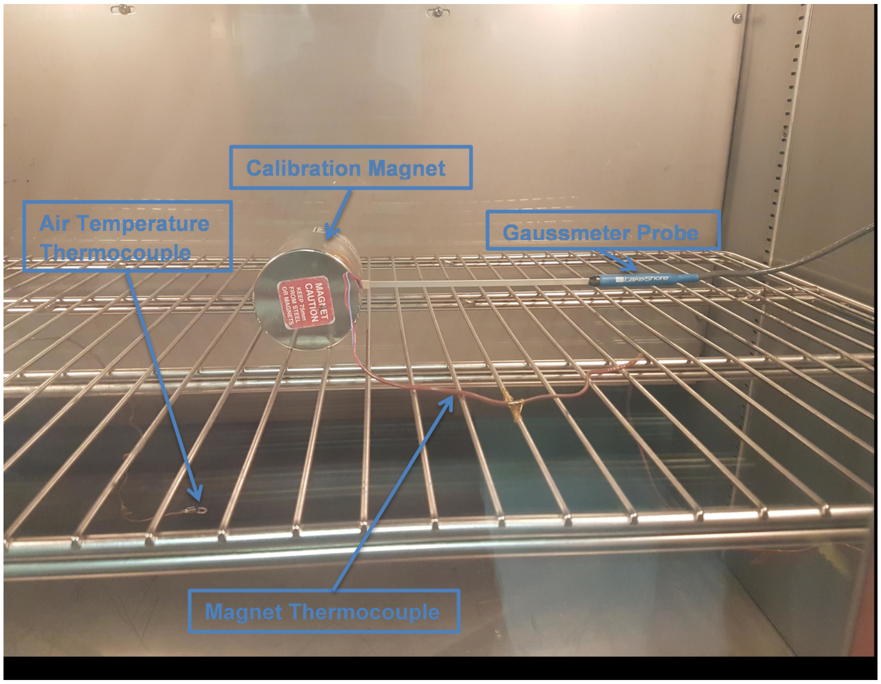

Figure 3: Experimental test set up 3

The method used during the second experiment is as follows,

- The temperature will be raised in 4°C increments at a ramp rate of 1°C per minute.
- Each temperature increase will be followed by a 10 minute stabilisation step to allow for the entire mass of the assembly to stabilize at the same temperature.
- The Magnetic Field Strength will be measured initial after reaching the target temperature, after 5 minutes and after 10 minutes to generate an average.

4. RESULTS

4.1 ASSEMBLED MAGNET RESULTS

Table 1 shows the results collected from the described experiment. In addition to the Gauss level the time stamp has also been recorded in relation to the time of the Thermatron Chamber. This is so the measurement can be compare to an exact temperature from any of the 4 thermocouples by using Figure 4 which is a temperature plot over the course of the experiment downloaded from the Thermatron.

Table 1 – Table of Results

[illegible]	[illegible]							[illegible]				
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0
Time Taken					11:47	11:57	12:07	12:17	12:27	12:37		
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	-0.31888
Time Taken					12:50	13:00	13:10	13:20	13:30	13:40		
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	-0.61783
Time Taken					13:56	14:06	14:16	14:26	14:36	14:46		
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]				[illegible]	[illegible]	-0.87062
Time Taken					15:01	15:11				07:49		
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	-1.32062
Time Taken					07:53	08:03	08:13	08:23	08:33	08:43		
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	-1.67621
Time Taken					08:57	09:07	09:17	09:27	09:37	09:47		

The temperature plot over the course of the experiment downloaded from the Thermatron is as shown.

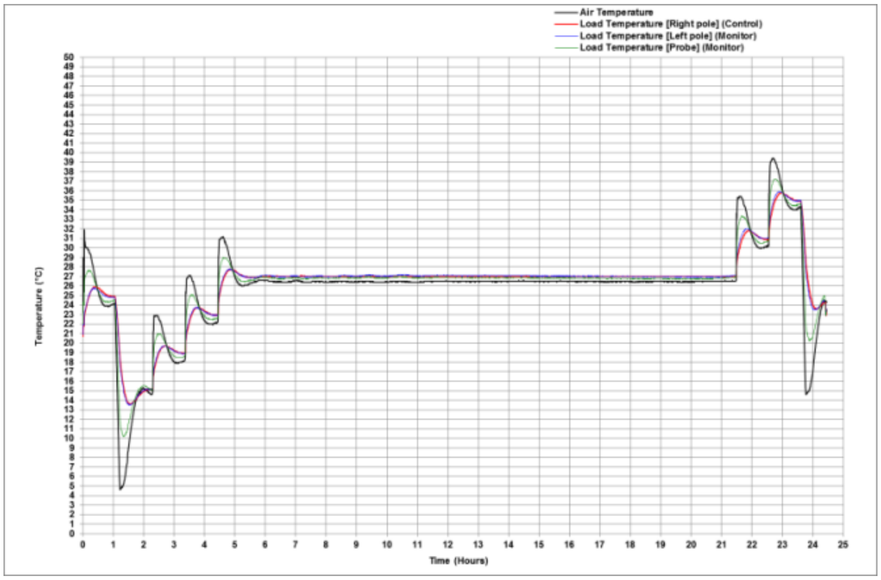

Figure 4 – Plot of Thermocouple Readout Temperatures

The last column of Table 1 shows the percentage change of the Gauss level as the temperature is increased from 15 to 35°C. It shows a decrease of 1.68%.

Figure 5 below is a plot of Temperature vs Gauss, by applying a trend line and taking the gradient of this line a value of 1.5 Gauss per °C is obtained. This value show that a change in 13.3°C is enough for a 20 Gauss shift in the flux density strength, which is equivalent to the tolerance of the Gauss rating.

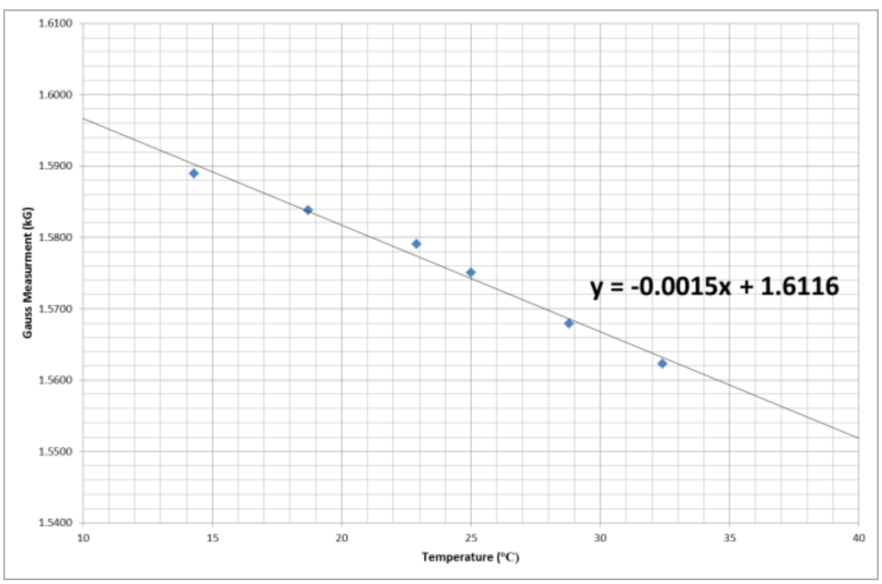

Figure 5 – Magnetic Field Strength (kG) vs Temperature (°C)

Further to above a graph of percentage change vs temperature (See Figure 6) was produced, which shows a percentage change of 0.09% per ˚C. Typical values for Neodymium are -0.08% to -0.12%[1] which is in line with the data gathered from the experiment.

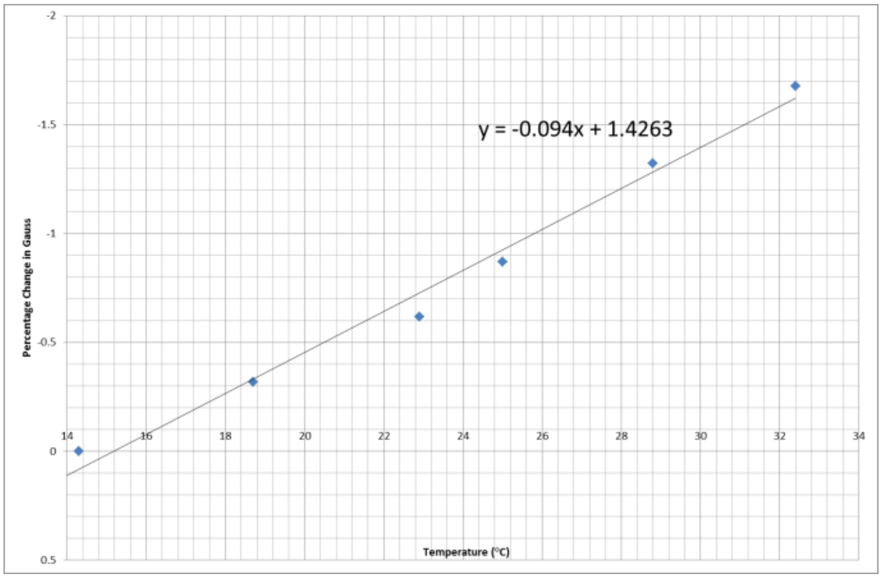

Figure 6 – Percentage Change in Magnetic Field Strength Reading vs Temperature (˚C)

4.2 GAUSS METER PROBE RESULTS

Table 2 below shows the results recorded when the probe was heated in the Thermatron. The Load temperature is the temperature of the probe. The column marked kG is the Magnetic Field strength reading in Kilo Gauss. The final column shows the percentage change from the initial value of 0.0136 @ 15ºC.

Table 2: Table of Results

Target Temperature	Load Temperature	Air Temperature	Time	kG	Percentage Change
15	15.6	15	14:18	0.0139	0
17	16.2	17	14:21	0.0139	0
19	20.2	19	14:24	0.0138	-0.7194245
21	22	22.2	14:27	0.0137	-1.4388489
23	23.5	23.8	14:30	0.0137	-1.4388489
25	25.2	25.5	14:33	0.0137	-1.4388489
27	27	27.3	14:36	0.0136	-2.1582734
29	29.4	29.4	14:39	0.0135	-2.8776978
31	31.1	31.2	14:42	0.0135	-2.8776978
33	33.4	33	14:45	0.0133	-4.3165468
35	35.5	35	14:48	0.0132	-5.0359712

Figure 7 below shows a plot of Magnetic Field Strength measurement shift. Using the gradient from the line of best fit a value of 3x10-5 kG (which is 0.03G) per ˚C is obtained.

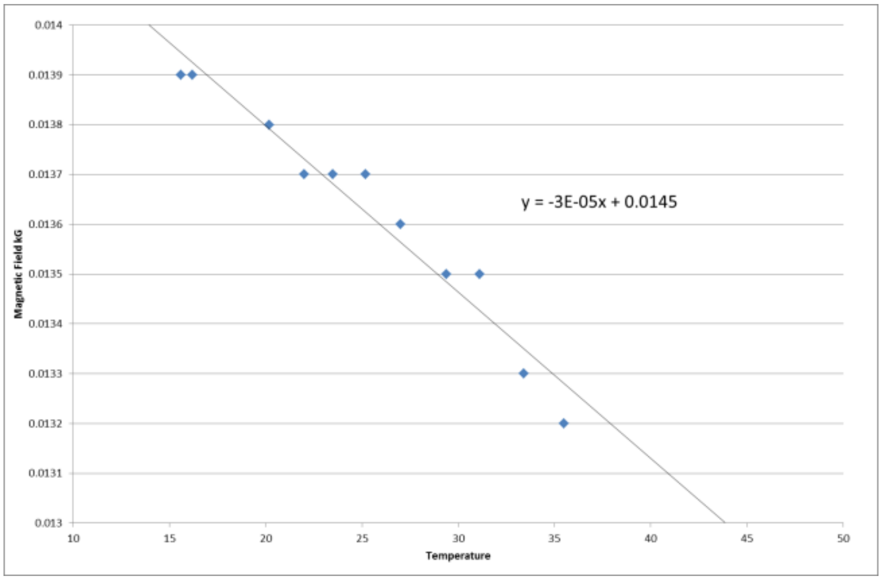

Figure 7 - Magnetic Field Strength (kG) vs Temperature (°C)

Even though I have included a percentage change column on my initial table it is not believed a graph of this data would be useful in this case as the magnetic field used during the test was of a small magnitude and therefore the measurement shift observed results in a great percentage change. If the field was of the same magnitude as the Pugsley magnet then the percentage change would be 3 orders less.

4.3 CALIBRATION MAGNET RESULTS

Table 3 bellow shows the Magnetic field strength measurements at different temperature as recorded by me during the experiment. The Magnet (Load) temperature was the temperature that the magnet was at when the readings were taken, there are 3 measurements of magnetic field strength in kilogauss followed by an average. The percentage change column at the end shows the change as the temperature was increased from 15°C to 35°C. The row marked 'INITIAL' was a result taken at ambient temperature before the chamber was turned on.

Table 3 – Table of Results

Temperature (Deg Celsius)			Gauss Measurement (kG)				
Target	Chamber (air)	Magnet (Load)	Initial	5 Mins	10 Mins	Average	% change
15	10.3	14.6	1.6499	1.6508	1.6514	1.6507	0
Time Taken			11:22	11:27	11:32		
19	19.1	18.4	1.6517	1.6514	1.6511	1.6514	0.042406
Time Taken			11:56	12:01	12:06		
INTIAL	22.6	24.8	1.6489			1.6489	-0.10904
Time Taken			10:43				
23	26.5	23.4	1.6503	1.6495	1.6488	1.6495	-0.07068
Time Taken			12:03	12:08	12:13		
27	31.1	27.7	1.6482	1.6471	1.6465	1.6473	-0.20799
Time Taken			12:17	12:22	12:27		
31	36.1	31.5	1.6448	1.6442	1.6437	1.6442	-0.39175
Time Taken			13:58	14:03	14:08		
35	37.4	34.8	1.6426	1.6417	1.6415	1.6419	-0.53109
Time Taken			14:12	14:17	14:22		

Using the results from table 3 a plot of percentage change vs temperature change was generated. (See Figure

8 below)

After plotting the graph it made obvious that the result collected for 19°C was anomalous as it as showing an increase in magnetic field strength as temperature was increased, this does not fit the established pattern. Therefore I have marked this point in red on the graph and omitted it from using it when plotting the line of best fit.

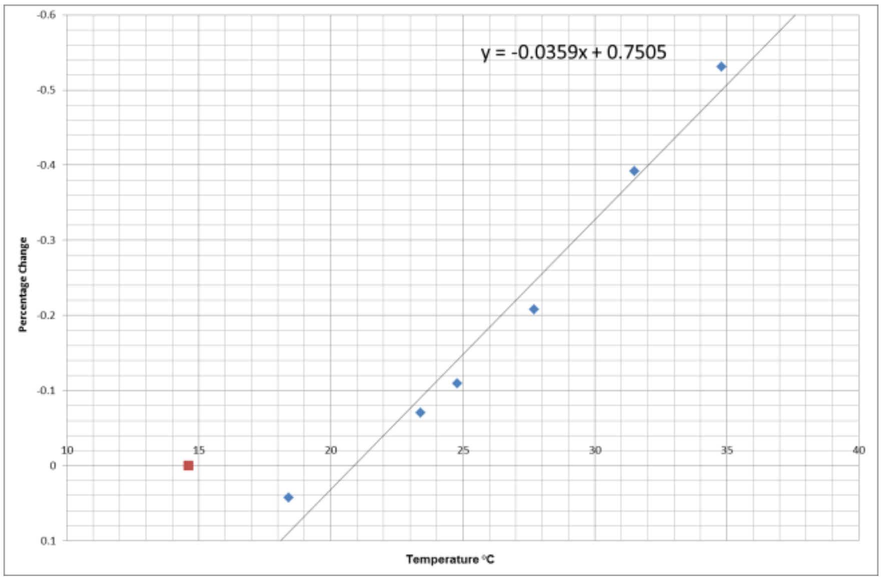

Figure 8 – Percentage Change vs Temperature (°C)

The results above in Figure 8 conform to the established pattern that we see in the first experiment. By taking the gradient of the line of best for a value of 0.036% is gained for the temperature coefficient of the magnet. Typical values of temperature coefficient for Sumerian cobalt magnets are 0.04% per °C this is very close to our measured temperature coefficient of 0.036% telling us our experiment is giving us results in line with the rest of the engineering community. This helps prove the experiment test method and results valid.

Taking the gradient of the line (percentage change per °C) and comparing it to the first experiment we can calculate a percentage difference between the two magnets. $(0.0359 \div 0.094) \times 100 = 42\%$. This is a useful number to consider; it tells us that the calibrations magnet's temperature coefficient is 42% lower than that of the magnet assembly

5. CONCLUSION

This experiment shows that the temperature variation is a cause for concern. The percentage tolerance of field strength is 1.282% and therefore with a variation of 0.09% per °C it would only take a 15°C shift to create a shift the equivalent size of the tolerance. By looking at the average max and min outside temperatures for Chelmsford for the past year, it was calculated that on average there is a temperature shift daily of 5.38°C [2]. This is enough to cause a magnetic field reading shift of just over -8G, which is just under -0.5% or 39% of the tolerance. In the summer months this temperature variation can reach as much as 8°C meaning a Gauss shift of -12, -0.72%, or 56% of the tolerance.

In conclusion it is suggested correcting for the measurement error evidently displayed above in the results by using the graph generated to 'correct' the measurement. Using such a graph would require every magnet before being Gauss tested to be linked to a thermocouple and its temperature recorded, and then the gauss reading could be adjusted using the graph as a reference to a 'set' temperature value e.g. 25°C.

The Gauss meter probe experiment validated the previous experiment and showed that the shift in the measurement of Magnetic Field Strength is not of a significant level and will not be enough cause a systematic error in size above the measurement accuracy of the experiment set up. Therefore the results of the previous experiment do not need to be corrected and any further experiments under taken this this does not need to be taken into account.

The calibration magnet experiment shows that the first experiment is valid and that the results gained form can be used in an updated work procedure. The results from the Calibration magnet experiment can also be use independently when using the calibration magnet for set up or any other reason where the measurement may be effected by ambient temperature.

5.1 EXRATAPOLATION OF RESULTS

Extrapolating the results of the first experiment to simulate the effective gauss drop at an operating temperature of 50°C is shown below. This is the temperature a magnet assembly could reach during magnetron operation. The graph (Figure 9) bellow shows this extrapolation.

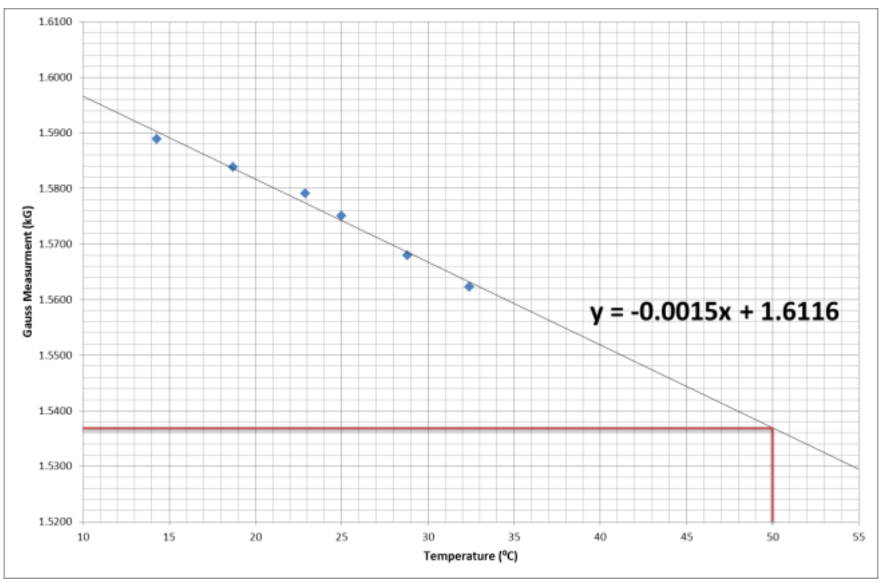

Figure 9 - Magnetic Field Strength (kG) vs Temperature (°C) - EXTRAPOLATED

Following this extrapolation it is predicted that the Gauss level at 50°C would 1.5370kG. This is a drop from room temperature operation (1.5740kG) of 0.371kG. This can also be expressed as a percentage drop of 2.35%. This drop in magnetic field strength is nearly double (183%) the drop the tolerance (20G, 1.282%) allows for. In my opinion this concern should be relayed to the customer to confirm they understand that this drop occurs and that they are accounting for that in their system.

6. ACKNOWLEDGEMENTS

Authors have no conflict of interest relevant to this article.

7. REFERENCES

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